

# Science and Technology Strategy for the Future

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## Fermilab's Strategic Plan (Updated July 2016)

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*This document is adapted from the Fermi National Accelerator Laboratory FY 2016 Annual Lab Plan, submitted to the U.S. Department of Energy Office of Science in July 2016. The Annual Lab Plan format is prescribed by DOE and the ALP document is written for DOE staff members, whereas this document has been edited to provide an overall summary of Fermilab's strategic plan to lab employees and users.*

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## Our Mission

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Fermi National Accelerator Laboratory is America's particle physics and accelerator laboratory. Fermilab's 1,800 employees and more than 2,600 users drive discovery in particle physics by building and operating world-leading accelerator and detector facilities, performing pioneering research with national and global partners, and developing new technologies for science that support U.S. industrial competitiveness.

Fermilab's science strategy for the future delivers on the U.S. particle physics community's goals as outlined in the Particle Physics Project Prioritization Panel's 2014 report<sup>1</sup>. The strategy's primary ten-year goal is a world-leading neutrino science program anchored by the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). The flagship facility comprised of LBNF and DUNE will be the first international mega-science project based at a Department of Energy national laboratory, and is the largest new particle physics project being undertaken anywhere in the world since the Large Hadron Collider at CERN.

Fermilab operates the nation's largest particle accelerator complex for particle physics, producing the world's most powerful low- and high-energy neutrino beams. It integrates U.S. universities and national laboratories into the global particle physics enterprise through its Large Hadron Collider (LHC) programs, neutrino science and precision science programs, and dark-energy and dark-matter experiments. Large-scale computing facilities drive research in particle physics and other fields of science. The laboratory's R&D infrastructure as well as its engineering and technical expertise advance particle accelerator and detector technology for use in science and society. Fermilab's partnerships and technology transitions programs, including the Illinois Accelerator Research Center, leverage this expertise to apply particle physics technologies to problems of national importance in energy and the environment, national security, and industry.

## Our Science and Technology Strategy for the Future

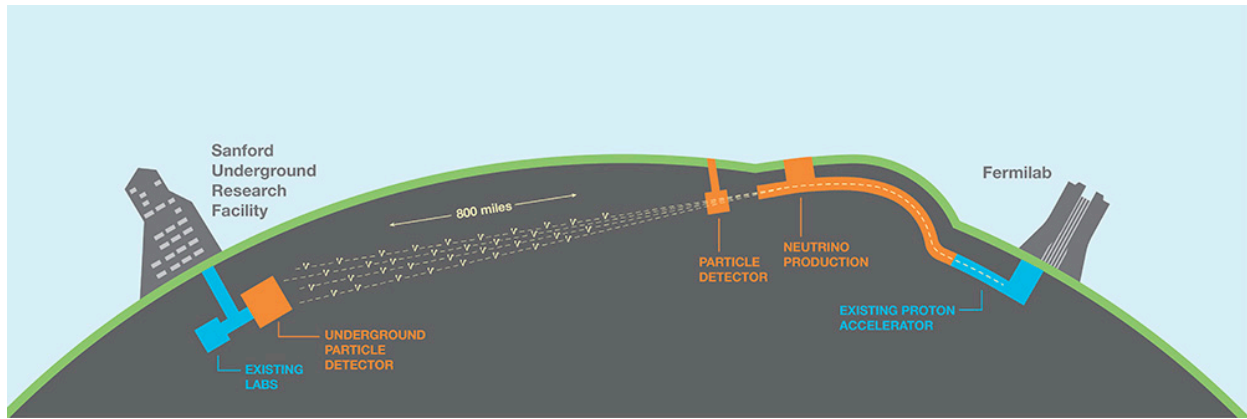
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Fermilab's science strategy for the future has as its primary ten-year goal a world-leading neutrino science program led by LBNF and DUNE and powered by megawatt beams from an upgraded and modernized accelerator complex. This national flagship particle physics initiative will be the first-ever large-scale international science facility hosted by the United States. Identified by the U.S. particle physics community in its consensus P5 report as the highest-priority domestic construction project in its timeframe, LBNF/DUNE is attracting global partners willing to invest significant financial, technical, and scientific resources. Over the next five years, a program that includes current and near-term neutrino experiments and an R&D platform that serves the wider neutrino physics community will drive the development of capabilities and bring together the international community needed for LBNF/DUNE.

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<sup>1</sup> <http://www.usparticlephysics.org/strategy.html>

Fermilab's success in operating the world's most powerful low- and high-energy neutrino beams, its core scientific and technical capabilities, its project management expertise, and its international reputation as an excellent scientific partner are making it the destination of choice for the world's neutrino researchers.

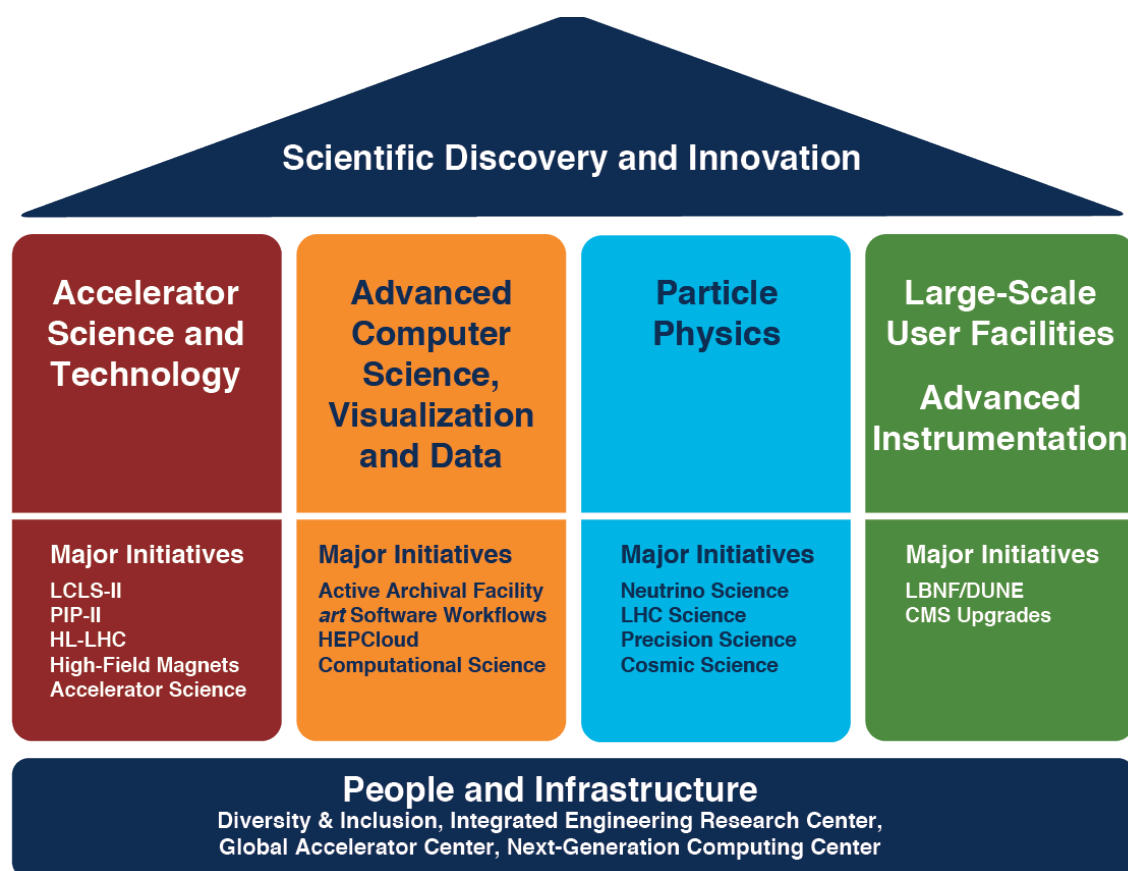


Artist's rendering of the Long-Baseline Neutrino Facility (LBNF) that will send a very intense beam of neutrinos 800 miles to a massive liquid-argon detector located deep underground in the Sanford Underground Research Facility in South Dakota.

As the country's particle physics and accelerator laboratory, Fermilab is moving forward with new experiments, new international and national partnerships, and R&D programs that support all of the science drivers identified in the P5 report:

- Over the next decade Fermilab will continue to be the leading U.S. center – and the second leading center in the world – for Large Hadron Collider science, enabling leading roles for U.S. scientists in future LHC discoveries and driving key contributions to upgrades of the LHC accelerator and the CMS detector.
- The start of the Muon g-2 and Mu2e experiments will turn Fermilab into the world center for the study of muons, particles whose properties may open a window onto new physics.
- Fermilab will support the community-endorsed diversified approach to dark matter detection, including key roles in the Generation 2 dark matter projects.
- The laboratory's leading role in the Dark Energy Survey, supporting roles in its successor experiments, and involvement with the South Pole Telescope will ensure continued U.S. leadership in the study of cosmic acceleration.
- In partnership with academics from nearby universities, Fermilab will support Illinois as a world center for advanced accelerator research with a suite of unique test facilities and R&D programs that will drive major advances in accelerator science and technology.

Fermilab's four core capabilities, described below, define the scope of the laboratory's science and technology strategy. Major initiatives identified within each of the four core capabilities represent the focus areas for the majority of the laboratory's time and effort over the next 10 years. A final "Building for Science" thrust describes additional major initiatives in people, infrastructure and R&D that support strategy accomplishment. The graphic on the next page illustrates how the lab's core capabilities and major initiatives comprise the strategy focused on scientific discovery and innovation.



## Our Core Capabilities

As defined by criteria established by the U.S. Department of Energy Office of Science (DOE-SC), Fermilab has four core capabilities that support the DOE-SC scientific discovery and innovation mission:

1. Particle physics
2. Large-scale user facilities and advanced instrumentation
3. Accelerator science and technology
4. Advanced computer science, visualization, and data.

The laboratory's four core capabilities are leveraged to deliver on DOE science priorities. High-intensity particle beams are used to answer compelling questions in neutrino science, and reveal new physics phenomena through high-precision tests of the Standard Model of particle physics. High-energy particle beams are used to discover new particles and probe the architecture of the fundamental forces of nature. Underground experiments as well as ground- and space-based telescopes are used to uncover the natures of dark matter and dark energy and probe the cosmic microwave background. The 2014 report of the Particle Physics Project Prioritization Panel (P5) identified the long-term science priorities for the U.S. particle physics community, and the laboratory is executing its strategic plan in alignment and coordination with P5, with DOE, and with the science community.

## Particle Physics

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Fermilab's science strategy enables a diverse science program with major discovery potential, from the science of neutrinos and the Large Hadron Collider, to the search for dark matter and anomalies in precision science, to the study of dark energy. To realize this strategy, the laboratory is advancing major initiatives in neutrino science, LHC science, precision science, and cosmic science. The overarching goal is to maintain and enhance a world-leading program that serves the needs and scientific goals of the U.S. and international particle physics community.

### Neutrino science

The revolutionary discovery that neutrinos can change from one type to another—and hence have mass—sparked a global initiative to investigate the phenomenon known as neutrino oscillations. The scientific community's vision for the future of U.S. particle physics is laid out in the P5 report and envisions Fermilab as the most advanced and diverse accelerator-based neutrino facility in the world. The community will achieve this ambitious goal by completing major upgrades to Fermilab's accelerator complex to deliver megawatt particle beams, building a new suite of three on-site neutrino experiments that will also serve as a test bed for advanced neutrino detectors, and leveraging international partnerships to construct the flagship international LBNF/DUNE facility. Over the next 10 years Fermilab's neutrino user community is expected to grow to more than 1,000.

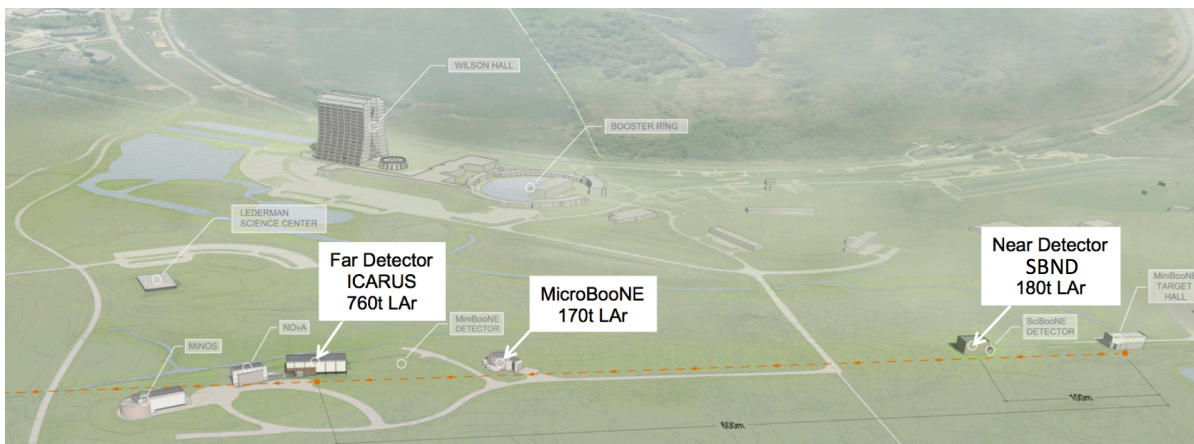
Fermilab is the one facility in the world that simultaneously operates two accelerator-based neutrino beams. These two intense beams drive an ensemble of experiments that study the detailed properties of neutrinos at both low and high energies and over both short and long distances. The first results of the NOvA experiment, based on 8% of its planned data set, hint at a normal neutrino mass hierarchy and CP violation effects that enhance the appearance probability for electron neutrinos. The continued success of the currently operating experiments and of the next generation of neutrino science projects depends critically on beam delivery. Accelerator improvements underway now, and even more ambitious upgrades planned for the next decade, will guarantee Fermilab's pre-eminence as the world's source of accelerator-driven neutrino beams for the next 20 years. The first of these upgrades, the Proton Improvement Plan (PIP), will more than double the number of protons used to make low-energy neutrino beams and increase proton beam power for high-energy neutrino experiments to 700 kW. The next accelerator upgrade (PIP-II) will replace the lab's existing 40-year-old linear accelerator with a new one based on superconducting RF cavities. PIP-II will increase the proton beam intensity for high-energy neutrino experiments to 1.2 MW before 2025, and will provide a platform for a future increase of the proton beam intensity to 2 MW for experiments envisioned beyond 2025.

For the short-baseline neutrino program a three-detector suite of experiments being built on the Fermilab site has the potential to make a groundbreaking discovery: the discovery of a fourth type of neutrino, the so-called sterile neutrino. An international team is preparing three detectors based on liquid-argon time-projection-chamber (TPC) technology with the goal of bringing all three online by 2018. Besides definitively addressing time-critical physics, this program will also provide an important platform for detector development and international coordination towards LBNF/DUNE. The first in this succession

is the MicroBooNE experiment, using a 170-ton detector that began taking data in 2015. While pushing towards significant advances in the liquid-argon TPC technology, MicroBooNE will also produce the first measurements of low-energy neutrino interactions in argon. By 2018 two additional detectors will have come online: the Short Baseline Neutrino Detector (SBND) that will be closest to the neutrino source; and the ICARUS T600—the largest liquid-argon TPC in the world—that will be brought to Fermilab after refurbishment at CERN.

Although the future short- and long-baseline neutrino programs involve multiple scientific collaborations that have distinct scientific goals, synergies in liquid-argon TPC technology and personnel provide coherence. The two programs together provide a coordinated approach to addressing some of the most fundamental questions about neutrinos but also provide a means to grow the technical expertise necessary to achieve success. The integrated program managed and enabled by facilities and staff at Fermilab will provide groundbreaking opportunities in research while also developing the expertise, technology, and computing required for the long-term program.

The ultimate goal of Fermilab's neutrino science strategy is the operation of the LBNF/DUNE program that will serve more than 1,000 users annually. This new large-scale user facility is a separate major initiative and is described on page 11.



*The new international short-baseline neutrino program at Fermilab that will include three liquid-argon detectors on the Booster neutrino beam line: SBND at 110m, MicroBooNE at 470m, and the ICARUS T600 detector at 600m from the Booster neutrino source.*

## LHC science

The Large Hadron Collider (LHC) at CERN is currently the only machine that produces the Higgs boson in sufficient quantities for study, and is a critical component of the multifaceted explorations of dark matter and the unknown—three of the key science drivers identified in the P5 report. Fermilab's four core capabilities allow the laboratory to play a significant role in driving LHC science over the next ten years through leadership roles in the CMS collaboration and technological contributions to the LHC accelerator and CMS detector upgrades—the first phase of which was identified in the P5 report as the U.S. community's highest-priority international construction project. Looking farther ahead, Fermilab plays critical roles in carrying out long-term R&D for accelerator technology and the physics program of future colliders.



Fermilab's continued participation in the international CMS experiment will ensure the collaboration's scientific success throughout LHC Run 2 (2015-2018) and Run 3 (2021-2023). The laboratory provides scientific leadership through contributions of its approximately 60 scientists to publication of innovative analyses of CMS data, technical and managerial contributions to detector upgrades and operations, and maintenance and continuing development of computing facilities and software infrastructure. As of September 2016, Fermilab scientist Joel Butler is also providing scientific leadership as the elected spokesperson for the 3000-member international CMS collaboration.

Fermilab has proposed making the CMS Center a DOE-SC national user facility that promotes U.S. scientific leadership at the LHC by supporting over 1000 users through its LHC Physics Center (LPC), Remote Operations Center, and dedicated computing facilities. In this context, the LPC already provides a vibrant on-shore academic environment focused around the LHC that includes tutorials, seminars, colloquia, visiting theorists, and organized and informal discussions. The annual LPC-hosted CMS Data Analysis School is crucial for training the newest members of the U.S. particle physics community, and the LPC Distinguished Researcher program is critical for maintaining a core group of physicists with diverse expertise at the LPC. The proposal to make the CMS Center a national user facility is currently under review by DOE-SC.

## Precision science

Experiments that study the properties of muons with high precision have the potential to elucidate the physics that leads to a low-mass Higgs boson, indicate the existence of new dark sectors responsible for dark matter, shed light on non-standard neutrino interactions, and indirectly probe energy scales as high as  $10^4$  TeV. Muon physics was identified by the P5 report as a critical component of the science driver to "explore the unknown" and the strategy correspondingly endorsed the construction of a Muon Campus at Fermilab that includes a new muon beam and two forefront experiments. By 2017 the Muon g-2 experiment will use the new muon beam to carry out the highest-precision measurement of the anomalous magnetic moment of the muon, and by 2021 the Mu2e experiment will be searching for charged-lepton-flavor violation using muons. The Muon Campus program already hosts 351 users from 51 U.S. and international institutions.

To realize the vision of a Muon Campus, Fermilab is constructing the world's brightest muon source, refurbishing the Muon g-2 storage ring into a first-in-class technical instrument, and building the Mu2e project. The new muon source will deliver a muon flux to the Muon g-2 experiment that is 20 times greater than that achieved for the previous experiment at Brookhaven National Lab. The refurbished Muon g-2 storage ring will allow for a measurement of the muon's magnetic moment that is a factor of four more precise than previously achieved. The Mu2e apparatus will allow for a factor of 10,000 improvement in the search for charged-lepton-flavor violation. Building and operating these facilities is bringing together expertise from particle, nuclear, and atomic physics. Fermilab staff designed most aspects of the technical instrumentation for Muon g-2 and Mu2e, and through their leading roles in the two experiments' scientific collaborations defined the physics program of the Muon Campus. The laboratory's strong lattice gauge theory group is deeply embedded in improving the Standard Model



calculation of Muon g-2 so that the precision in the expected value will shrink in relation to the expected improved precision in the experimental value.

Fermilab's accelerator science and technology core capability includes the ability to develop technologies to accelerate, characterize, and manipulate the particle beams that are required for precision science. For example, experimental, computational, and theoretical research on the physics of particle beams has been important in designing beam delivery systems for Muon g-2 and Mu2e. The configuration of the Fermilab accelerator complex is unique in its ability to simultaneously deliver beam to the muon and neutrino programs, and the PIP-II upgrade will support a factor of ten enhancement in beams delivered to a possible second generation Mu2e experiment that would capitalize on knowledge gained in the initial Mu2e incarnation. Fermilab's core capability in advanced computer science, visualization, and data is critical to the success of this program since the multi-petabyte data sets are orders of magnitude larger than the previous round of these experiments.

The Muon Campus will be a significant addition to Fermilab's scientific user facility and will advance the mission of the DOE Office of High Energy Physics with the ability to deliver significant and potentially revolutionary results. The program has helped foster integration by driving closer collaboration with Brookhaven and Argonne national laboratories, with the NSF through a Major Research Instrumentation grant to provide the detector package for Muon g-2, and with six other nations to optimize the use of the resources available in achieving our scientific goals.

## Cosmic science

The P5 report identified the new physics of dark matter, understanding cosmic acceleration, and pursuing the physics of neutrinos as three of the primary science drivers in particle physics, each of which is addressed by the study of cosmic science. With its strong particle astrophysics program and advanced infrastructure, Fermilab is a leader in all of these areas, and an active participant in the DOE Cosmic Visions planning process. Over the next decade, the laboratory will continue to explore cosmic acceleration through large-scale surveys, build the next generation of detectors for the cosmic microwave background, and advance the search for dark matter using select technologies.

The Dark Energy Survey (DES), which recently finished its third year of data taking, is the world leader in exploring the mysterious phenomenon of dark energy, with Fermilab



*One image from the Dark Energy Survey showing NGC 1703 (large galaxy in the foreground) and thousands of more distant galaxies. DES uses the spatial distribution of these galaxies along with hundreds of millions of others in the DES survey to study dark energy.*

managing operations and leading analysis of DES data. The first cosmology results on weak lensing were published this year. DES has observed more than 150 million galaxies and discovered more than twice the number of Type IA supernovae than the largest existing published sample. DES has also doubled the number of known ultra-faint dwarf galaxy candidates where scientists can look for products of dark matter annihilation. Recently, Fermilab funded an LDRD proposal to enable DES to search for optical counterparts to gravity-wave sources as new probes for dark energy, a decision that proved prescient with the groundbreaking announcement of the detection of gravity waves by the Laser Interferometer Gravitational Wave Observatory (LIGO) in February 2016.

Over the next ten years, Fermilab will play important roles in two cosmic surveys strongly endorsed by P5, the Dark Energy Spectroscopic Instrument (DESI) and the Large Synoptic Survey Telescope (LSST). For DESI, Fermilab will provide scientific management, a massive image corrector system, the online database, software to ensure that DESI observes the correct targets, and detector packaging and testing. Because of its experience leading the Sloan Digital Sky Survey and DES, Fermilab has a unique understanding of the challenges facing LSST, and will be an active participant in the LSST Dark Energy Science Collaboration. The laboratory is currently developing a software framework for dark energy science at LSST based on the one used by DES, leveraging Fermilab's core capability in advanced computer science.

Motivated in part by ideas generated by the Fermilab Astro Theory Group, the Cosmic Microwave Background (CMB) has become the most precise tool for understanding cosmology with significant implications for particle physics. The P5 report endorsed DOE participation in CMB-S4, a U.S.-led program to build a next-generation CMB experiment and enable new constraints on the physics of inflation, neutrinos, and dark energy. Fermilab plans to become a leader in CMB studies over the next ten years. Building off expertise developed for DES, Fermilab is now leading the design and fabrication of the new camera for the South Pole Telescope (SPT). A recent LDRD award has allowed Fermilab scientists to begin developing next generation CMB detectors and instrumentation, positioning the laboratory for a leading role on CMB-S4.

Fermilab is committed to understanding the nature of dark matter and plays a key role in the second-generation (G2) dark matter projects now underway. Over the next several years, Fermilab will co-lead the SuperCDMS-SNOLAB project with SLAC, building on world-leading limits on low-mass dark matter released in the past year. Fermilab is also a strong contributor to the LUX-Zeplin (LZ) experiment at SURF, providing cryogenic and process control engineering to safely manage the 10 tonnes of liquid xenon required by the detector. The LZ experiment will improve on the current best sensitivity for high-mass dark matter by a factor of a hundred. Rounding out the G2 program, Fermilab is contribution to the Axion Dark Matter Experiment (ADMX) that searches for axions that scatter in a strong magnetic field and convert into microwave photons. Supported in part by an LDRD, Fermilab's core capability in accelerator science and technology will be used to study high-quality-factor resonant cavities and single microwave photon detectors, enabling the high-mass axion search phase of ADMX.

Fermilab's detector R&D program has supported many efforts in cosmic science. Fermilab led the development of the COUPP/PICO bubble-chamber dark-matter detectors and leveraged its DES experience to pioneer the use of CCDs as very-low-threshold detectors in the DAMIC experiment, with both efforts leading to recent world-leading results. The DAMIC effort has led in turn to LDRDs to develop lower-noise CCDs and to search for coherent neutrino scattering at nuclear reactors. Fermilab will continue R&D towards next-generation detectors for cosmic science, for example developing cryogenic systems for superconducting detectors with sub-Kelvin capabilities.

Cosmic science provides a showcase for the benefits of broad collaboration among DOE laboratories and universities. As noted by P5, particle physics drivers are intertwined, and cross-project expertise is required to extract the most science from the data. Fermilab scientists have already been leading these efforts. For example, the dwarf galaxies discovered by DES have led to dark matter constraints, and joint analyses of the DES and SPT data sets have placed new constraints on dark energy and gravity at large scales. Over the next decades, Fermilab will act as a central platform and host for understanding cosmic science data, maximizing the scientific output of experiments in the field.

## Large-Scale User Facilities

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### LBNF and DUNE

Fermilab's science strategy sets the trajectory for the United States to lead the world in accelerator-based neutrino science, anchored by the billion-dollar-class international LBNF/DUNE major initiative. The laboratory has demonstrated excellence in building and operating long-baseline neutrino experiments starting with the MINOS experiment and continuing with NOvA. These projects, together with Fermilab accelerator upgrades, detector R&D to advance liquid-argon time projection chamber (TPC) technology, and the short-baseline neutrino program set the stage for a flagship international neutrino program based on LBNF and DUNE.

Coupling a massive 40-kiloton underground liquid-argon TPC detector with the world's most intense neutrino beam, LBNF/DUNE offers unparalleled opportunities for discovering CP violation in the neutrino sector and unprecedented sensitivity to proton decay, supernova neutrinos, and atmospheric neutrinos. Fermilab, working with international, national laboratory, and university partners plans to host this new long-baseline program that will include intense neutrino and antineutrino beams, conventional facilities at both Fermilab and the Sanford Underground Research Facility in South Dakota, an advanced (near) detector on the Fermilab site, and a massive liquid-argon TPC (far) detector and associated cryogenics at Sanford Lab. A neutrino experiment of this scale and capability has never before been realized. LBNF/DUNE advances the P5 plan by establishing the first phase of this facility with a new beamline and infrastructure for a far detector sited deep underground in the 2020s.

To advance LBNF/DUNE the U.S. and CERN signed a bilateral international cooperation agreement and approved the subsequent Neutrino Protocol. In this context, CERN committed to build the first cryostat for LBNF. To support the DUNE prototyping effort, CERN is currently constructing cryogenics, cryostat,

beamline and conventional facility infrastructure for two protoDUNE detectors that are anticipated to be operational before the end of 2018. To deliver the international protoDUNE effort within this timeframe, Fermilab is working with Argonne National Laboratory, Brookhaven National Laboratory and Lawrence Berkeley National Laboratory as well as the 900-member DUNE collaboration, which includes members from more than 160 institutions in 30 countries as well as DOE- and NSF-funded institutions.

## CMS upgrade projects

Initiated in 2012 and targeting completion in 2018 for the start of LHC Run 3, the first significant upgrade of the CMS detector will allow collection of high-quality data at event rates and radiation levels three times higher than recorded in the LHC's first run. Fermilab is responsible for project management of the U.S. contribution to this upgrade project, which is jointly funded by DOE and NSF and includes upgrades of the forward pixel detector, the hadron calorimeter, and the trigger system. The project includes 30 university partner institutes (all part of the CMS collaboration) that account for 80% of labor and M&S expenditures and contribute to the success of the project by providing unique expertise.

A second and significantly more extensive upgrade of the CMS detector is required to handle the extreme data rates and associated radiation damage that the detector will face during the HL-LHC running period. The CMS collaboration is engaged in detailed planning and R&D activities for the second upgrade. The U.S. CMS collaboration and Fermilab will play a major role in several aspects of this upgrade, including construction of a new forward pixel detector, silicon strip tracker, endcap calorimeter, and track-based trigger. An aggressive, but achievable, upgrade timeline has been developed to meet CERN's HL-LHC timeline: design and prototyping through 2018; pre-production in 2018-2019; construction in 2019-2024; and installation and commissioning in 2024-2025. Together the two CMS upgrade projects constitute a major initiative for Fermilab.

Over the next several years the laboratory will work in conjunction with CMS, DOE, NSF, and university partners to define the role of Fermilab in the second upgrade. DOE CD-0 for the upgrade project was approved on March 7, 2016. The project is targeting CD-1 in FY17, and CD-2/3 in FY19 with a potential CD-3a in the middle of FY18 so that engineering and construction of large prototypes can proceed according to plan.

## Accelerator Science and Technology

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Fermilab's core capability in accelerator science and technology powers particle physics discoveries and makes significant contributions to research in other scientific disciplines. The laboratory's accelerator science and technology strategy is motivated by the P5 report, which identified the need for accelerated beams to investigate four of its five science drivers. Recommendations from the HEPAP accelerator R&D subpanel strongly endorse Fermilab's plans to pursue an aggressive research program funded by DOE's General Accelerator R&D (GARD) program. The program includes superconducting radio-frequency (SRF) acceleration technology, high-field superconducting magnets, beam physics, and high-power targets. Over the next 10 years, Fermilab will make significant contributions to CERN's HL-LHC

accelerator upgrade, the PIP-II project that upgrades Fermilab's accelerator complex for LBNF/DUNE, and SLAC's LCLS-II project. The following five major initiatives comprise the laboratory's strategy for accelerator science and technology.

## **LARP and the HL-LHC upgrade**

CERN is planning a major upgrade of the Large Hadron Collider that will increase instantaneous luminosity by ten times compared to the LHC's luminosity in 2012. The High-Luminosity LHC (HL-LHC) accelerator upgrade, scheduled for 2024-2025, is a major initiative for Fermilab that requires significant advances in accelerator science and technology. Fermilab is leading the U.S. contribution to HL-LHC R&D through the ongoing LHC Accelerator Research Program (LARP), which is the U.S. national program that funds accelerator research in support of the LHC. LARP is expected to complete its HL-LHC R&D effort within the next two years following the delivery of prototypes for the HL-LHC upgrade. A natural goal for LARP after delivering HL-LHC prototypes will be to concentrate on R&D for the High Energy LHC, HE-LHC [see 3.3.4]. The U.S. HL-LHC Accelerator Upgrade Project (HL-LHC AUP) will deliver the components to CERN that will encompass the U.S. contribution to the HL-LHC upgrade. Fermilab will lead this project, and will work in conjunction with DOE and CERN to define deliverables. The project is expected to achieve CD-1 in FY17, and a consolidated CD-2/CD-3 in FY18. Achieving CD-3a in advance of FY18 for long-lead time procurements such as superconductor, assembly tooling, and magnet parts is under consideration to meet the delivery schedule requested by CERN.

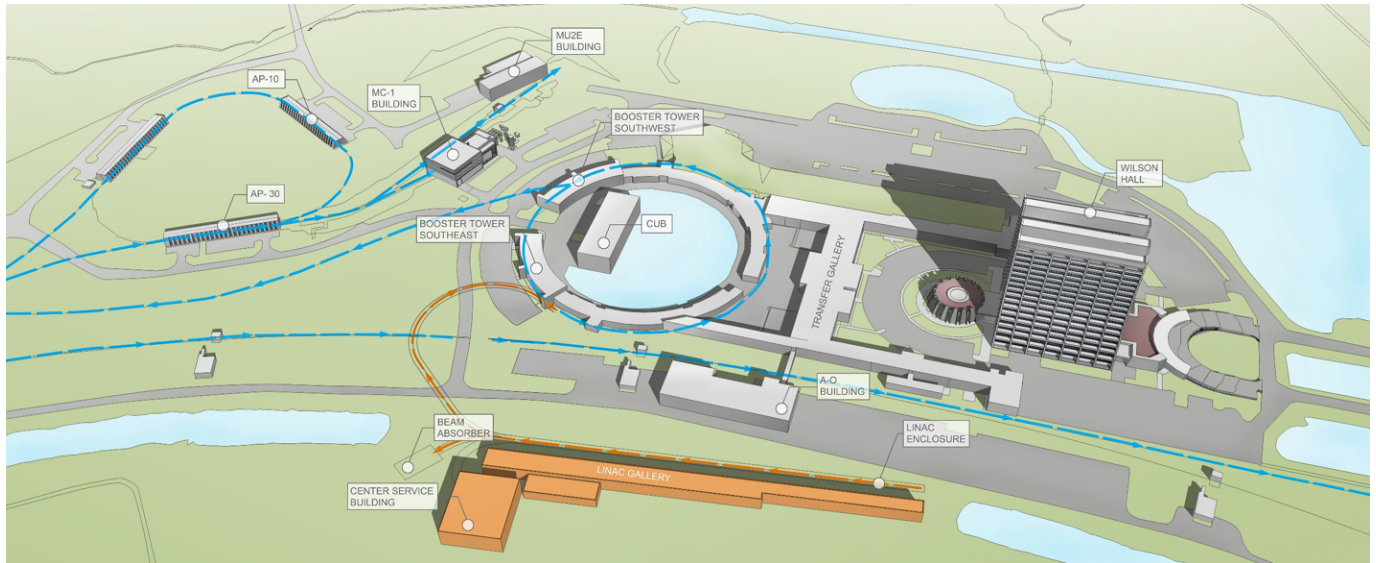
## **PIP-II upgrade to the Fermilab accelerator complex**

Over the next ten years a two-stage upgrade will increase the power of Fermilab's proton beams, enabling the laboratory's flagship neutrino and precision science programs. The Proton Improvement Plan (PIP) currently underway will increase the beam power delivered to the NuMI facility to 700 kW by 2017. Recent achievements include record proton flux, increased uptime, and improvements in beam delivery that resulted in record beam intensities to both the Booster and NuMI neutrino beams. Following the completion of PIP, the Fermilab complex will be unique in the world in its ability to deliver beams simultaneously to both neutrino and precision science programs. The PIP-II project, a major initiative for Fermilab, will further increase the power to 1.2 MW as required for LBNF/DUNE while enabling further performance enhancements to the precision science program. SRF is the only modern technology suitable for continuous-wave accelerators, as would be required for a second-generation Mu2e experiment.

The PIP-II project is supported by a comprehensive R&D program pursued as a joint collaboration between the U.S. DOE and the Indian Department of Atomic Energy. Over the next five years this program incorporates R&D aimed at demonstrating state-of-the-art performance in the PIP-II low-energy front end, and development of SRF systems required for acceleration of proton beams. Fermilab is working with Argonne National Laboratory to develop and build a low-frequency half-wave resonator SRF cryomodule for PIP-II. Argonne's expertise in this area is complementary to Fermilab's SRF capabilities. These major elements of the program are accompanied by comprehensive theoretical and experimental investigations of major loss mechanisms and beam instabilities in the laboratory's existing Booster, Main Injector, and Recycler proton accelerator complex. High-intensity targets and focusing



systems are crucial and R&D to improve them will be actively pursued. Advanced computer modeling and simulation of beams with space charge in realistic ring environments will benefit both the Fermilab accelerator complex upgrades as well as other existing accelerators.



*Conceptual design of the PIP-II upgrade, showing the location of the linear accelerator and service building relative to Wilson Hall.*

## LCLS-II and future SRF accelerators

At the center of Fermilab's accelerator technology activities is the superconducting radio-frequency program. SRF is the enabling technology for future-generation high-intensity accelerators that are at the core of DOE-HEP and the Office of Science mission. Fermilab has world-leading capabilities and infrastructure in SRF technologies following a sustained investment by DOE-HEP of approximately \$200M over the last decade. Currently, Fermilab's SRF program focuses on three major areas: production of LCLS-II cryomodules in close partnership with SLAC National Accelerator Laboratory and Thomas Jefferson National Accelerator Laboratory, directed R&D for PIP-II, and advanced accelerator R&D on basic SRF science and cavity development for future accelerators. The laboratory's SRF expertise is a key enabler of SLAC's LCLS-II accelerator project. Experience, knowledge, and infrastructure developed through the LCLS-II project will subsequently be applied to the lab's PIP-II project.

The Fermilab SRF program has led to major breakthroughs that dramatically increase SRF cavity efficiency ( $Q_0$ ) and hence reduce operating costs. LCLS-II is the first benefactor of this success, and the current LCLS-II design depends on transitioning these breakthroughs from R&D to production and operations. Fermilab plays a key role in this endeavor by providing overall technical leadership. A thorough understanding of the underlying physics is crucial to realize the full potential of these breakthroughs and to transfer benefits to all future SRF accelerators. Over the next few years, fundamental investigations into the physics of quality factor limitations at low and high fields will be

actively pursued in collaboration with laboratories (CERN, KEK, Thomas Jefferson National Accelerator Laboratory) and international and U.S. universities (for example Cornell University, Illinois Institute of Technology, Northern Illinois University, Northwestern University, and the University of Chicago). A primary goal is to decrease capital costs and operational cryogenic costs of future continuous-wave accelerators by a factor of two or more.

Fermilab has a nascent effort to develop detector technology for LCLS-II. The laboratory's Application Specific Integrated Circuit (ASIC) design group will collaborate with SLAC's detector development group to develop a new generation, very high readout speed X-ray detector for use at the LCLS-II facility. This effort will leverage experience gained by the Fermilab ASIC group in the development of high-speed readout chips for HEP silicon vertex detectors and in collaborative efforts with Argonne National Laboratory and Brookhaven National Laboratory in the development of X-ray detector systems for use at the Argonne Advanced Photon Source.

## High-field superconducting magnets

Fermilab is home to world-class facilities and R&D programs in high-field superconducting magnets that will be critical for future proposed large accelerators. For example, an upgrade of the LHC to higher energies, the HE-LHC, will require dipole magnets that produce unprecedented magnetic fields at a reasonable cost. To support efforts aimed at developing magnets for HE-LHC, the laboratory is well positioned in that it is the home institution for LARP. After the successful launch of the HL-LHC construction project for the LHC luminosity upgrade, it would be natural for LARP to apply its successful domestic and international approach to collaboration and focus on HE-LHC developments by initiating a directed high-field magnet R&D program with the goal of demonstrating 14-15 Tesla accelerator-quality superconducting magnets. A demonstration of 16 Tesla superconducting magnets may be possible, but depends on funding availability. Fermilab researchers will also collaborate with the national magnet development program and its goals to pursue generic technology development to evaluate high-temperature superconductor inserts with the possibility of producing fields of 20 Tesla or higher.

## Accelerator science

Over the next five years Fermilab will establish a fully operational test facility to address key questions related to intense beams for future, cost-effective accelerators. The facility will enable transformative accelerator science. The central component of the test facility will be the Integrable Optics Test Accelerator (IOTA), an innovative nonlinear storage ring that will include a proton and ion injector as well as a world-class high-brightness electron injector. Fermilab will complete construction and begin commissioning IOTA in 2017 by leveraging GARD funding together with LDRD funds, build community interest through university-lab partnerships, develop a focused science program via directed workshops, and produce a schedule for implementing the IOTA science program collaboratively with partners. IOTA scientific output will be critical to define the next steps in high-intensity particle beam development beyond PIP-II, and to establish novel approaches to advanced beam physics research.



## Advanced Computer Science, Visualization and Data

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Fermilab is continually expanding its capabilities for handling, storing, processing, and analyzing scientific data to meet the needs of the U.S. community's exciting and ambitious particle physics research program. To keep the community at the forefront of discovery and enable new directions in physics research, Fermilab pursues an advanced R&D program for software and computing solutions, specifically targeting the application of industry standards and emerging technologies. This strategy is based on a close partnership with the DOE Advanced Scientific Computing Research (ASCR) program to enable the particle physics community to take advantage of the latest developments in High-Performance Computing (HPC) and to contribute to the evolution of the National Strategic Computing Initiative towards exascale computing. The following four major initiatives comprise the lab's strategy for Advanced Computer Science, Visualization, and Data.

### The scientific workflow framework *art*

Software is an integral part of the scientific process and is at the heart of every experiment. From recording, storing, and retrieving detector data to performing physics reconstruction and analysis, software needs to be efficient and user-friendly to enable experiments to extract physics results. The scientific workflow framework *art* provides the community with a common software layer to store and access scientific data and to schedule algorithms in an efficient and convenient way. The system grows to meet the needs of individual experiments through minimal experiment-specific customizations that don't require expert knowledge. The software stacks for all of Fermilab's operating neutrino and muon experiments now use the *art* framework. NOvA has been using *art* for offline data handling and data analysis. MicroBooNE successfully started taking data in 2015, and uses the framework extensively for their online and offline data handling and processing. Fermilab will continue to evolve *art* to keep pace with major software and computing hardware developments like the increased diversity of grid, cloud, and supercomputer resources. These will require changes in the underlying framework but will benefit many experiments simultaneously, thus minimizing the effort required from each individual project. Furthermore, the community has started to benefit from derived products that are based on *art*, such as *artdaq*, a common data acquisition system, and LArSoft, a common reconstruction algorithm for liquid-argon neutrino detectors. The evolution of *art* and its software ecosystem is a significant cornerstone of Fermilab's strategy to enable future scientific workflows.

### HEPCloud: A new paradigm for particle physics computing

Particle physics requires copious computing resources to extract physics results. Such resources are delivered by various systems: local batch farms, grid sites, private and commercial clouds, and supercomputing centers. Historically, expert knowledge was required to access and concurrently use all these resources efficiently. Fermilab is pursuing a new paradigm in particle physics computing through a single managed portal (HEPCloud) that will allow more scientists, experiments, and projects to use more resources to extract more science, without the need for expert knowledge. HEPCloud will provide cost-effective access by optimizing usage across all available types of computing resources and will elastically expand the resource pool on short notice (e.g. by renting temporary resources on commercial clouds).

This new elasticity, together with the transparent accessibility of resources, will change the way experiments use computing resources to produce physics results. The CMS collaboration was amongst the first users of HEPCloud. CMS was able to increase its resources by 50 thousand cores (approximately 1/3 of CMS's world-wide available resources) by using Amazon Web Services cloud resources through HEPCloud for about one month. This enabled CMS to deliver more physics results for the physics conferences in Spring 2016 than were planned with non-HEPCloud resources. HPC facilities present an appealing option to be considered as an additional external resource for HEPCloud. Fermilab is in the process of engaging ASCR researchers and facilities experts to develop the necessary partnerships both for porting HEP applications to these resources and for developing software and security infrastructure to access them.

## **Active Archive Facility: Share Fermilab's data handling leadership with other communities**

Fermilab is a world leader in the handling of many petabytes of scientific data for the national and international particle physics community. This includes transferring large amounts of data into the Fermilab facility, archiving the data on Fermilab's exabyte-scale tape system, and using high-performance disk caches to provide efficient and secure access to the data, either locally or from off-site. A similar need for large-scale data handling has also recently arisen in other scientific disciplines. Fermilab's Active Archive Facility (AAF) will be developed to enable non-particle physics experiments and collaborations to benefit from Fermilab's leadership, expertise, and facilities. AAF will open Fermilab's storage, archiving, and data access capabilities to other research communities, with methods implemented to recover costs. The Simons Foundation is one of the first non-particle physics science organizations benefiting from AAF capabilities. Over one petabyte of genomics research data have been stored on tape media at the AAF and are securely accessible from around the world.

## **Computational science**

New computing architectures are emerging as a result of advancements in computing hardware. The exascale era of computing will drive these innovative hardware and software technologies. Particle physics will have to adapt so that its researchers can benefit from the increased performance of these architectures. Synergies between the DOE OHEP program and the DOE ASCR program will be essential to allow the U.S. particle physics community to take advantage of this new computing era. Fermilab will seed, cultivate, and coordinate cross-cutting development efforts between OHEP experimental programs and ASCR institutions to maximize the benefit from exascale computing. With a recently funded LDRD effort on "Exascale-era computing and HEP", Fermilab is starting on the path to evolve particle physics software and computing to be part of the exascale future.

## Building for Science: People, Infrastructure, Innovation

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Fermilab's strategy for supporting its four core capabilities is known as "Building for Science" and incorporates building a diverse and inclusive workforce, modernizing infrastructure at all levels, and investing in the Laboratory Directed Research and Development (LDRD) program. In the area of infrastructure, the Utilities Upgrade Project (UUP), which is half completed, includes replacement of the master substation and industrial cooling water piping backbone by FY 2019. This project addresses infrastructure needs for Fermilab as a large-scale user facility. The Integrated Engineering Research Center (IERC) is a major initiative that will transform the laboratory's core capability in particle physics. Two other major initiatives, the Global Accelerator Center (GAC) and the Next Generation Computing Center (NGCC), will transform the laboratory's core capabilities in accelerator science and technology and advanced computer science, visualization and data, respectively. These three centers complete the modernization of mission-driven infrastructure needs identified in the Fermilab Campus Master Plan.

### Infrastructure upgrades driven by the Fermilab Campus Master Plan

The Campus Master Plan, which presents a comprehensive approach to Fermilab's future infrastructure, has four primary objectives:

1. Construct sustainable infrastructure that will attract international investment and the brightest minds to the world's leading laboratory for accelerator-based neutrino science
2. Maximize productivity by establishing an atmosphere of *"eat-sleep-work to drive discovery"* that efficiently meets the needs of the scientific community
3. Integrate into one geographic area the entire life cycle of research, engineering, fabrication, and operations expertise for accelerators and detectors
4. Consolidate, centralize, and modernize to optimize operational resources, maximize efficiency, enhance communication, and foster succession planning

These objectives address the needs of the laboratory's core capabilities by providing facilities and infrastructure to close identified infrastructure gaps. More space will be available for project teams and international users associated with the flagship LBNF/DUNE initiative, and more high-bay space will be added for production of accelerator, detectors and other components. New buildings will be located where they will maximize resource utilization efficiency for projects and operations. State-of-the-art computing facilities will be available. Facilities will be modernized using modular walls and furniture for efficient reconfiguration. And short-term accommodations will be increased for a growing number of users and visiting scientists and engineers.

## Integrated Engineering Research Center

A world-leading science laboratory needs world-class facilities and infrastructure to support its program. Fermilab's campus master plan portrays a future envisioned as "a state-of-the-art particle physics laboratory that will host a vibrant, international community of employees and users on a safe, accessible site that celebrates and protects the natural environment." The Integrated Engineering Research Center (IERC) anchors the development of the laboratory's central campus. The IERC provides the interdisciplinary environment necessary for a world-class international neutrino science program by co-locating engineering and technical staff immediately adjacent to the main administrative building.

Currently in the conceptual design phase, the project will be a new start with project engineering and design funding anticipated in FY 2017. IERC construction is expected to begin in FY 2018. The project will transform the laboratory's core capability in particle physics by providing modernized infrastructure as well as a collaborative environment with laboratory and technical team spaces.



*Artist rendering of a conceptual design concept for the Integrated Engineering Research Center.*

## Global Accelerator Center

The Global Accelerator Center is envisioned as a mission-driven infrastructure improvement that will transform the laboratory's core capability in accelerator science and technology, thus sustaining the national and international accelerator science community for many years to come. At the same time as Fermilab's accelerator complex has transitioned from high-energy colliding beams to high-intensity proton beams for neutrino and precision science, the laboratory's accelerator scientists and technical teams have focused more on developing transformational accelerator technologies for use across the DOE-SC complex and around the globe. These transitions, combined with the condition and age of Fermilab's accelerator facilities, drive the need to consolidate core research functions and modernize key support facilities. The current lack of a modern, efficient, centralized space for accelerator scientists and key mission support staff reflects an infrastructure gap. A new building can bridge this gap by upgrading working conditions for more than 25% of the laboratory staff, and by providing a modern work space for visiting and collaborating national and international accelerator scientists. Co-locating accelerator scientists and their technical teams will allow better integration of the accelerator science, operations, and technology functions of the laboratory and will drive future national and international advances in accelerator science and technology.

## Next-Generation Computing Center

The Next-Generation Computing Center (NGCC) will transform the laboratory's core capability in advanced computer science, visualization, and data, allowing Fermilab to keep pace with rapidly developing technologies and changing scientific demands. The NGCC will support the major initiatives that have been identified for this core capability, including HEPCloud and the Active Archive Facility. Three critical components have been identified for the NGCC. The first is big data storage. This component will provide large disk storage, tape storage, and networking and will be located underground to protect systems and data from natural disasters. The second component will provide space needed for computing systems. This will include space for scientific computing and business computing systems that will be deployed using open-air, state-of-the-art, and green cooling systems. The third component of the NGCC will provide collaboration and meeting space that is currently unavailable at Fermilab's Feynman Computing Center. Computer scientists and their technical teams as well as collaborating scientists from around the world will benefit from the availability of small-group workspaces for collaboration, medium-sized meeting rooms, and a 300-seat auditorium. The laboratory is seeking non-DOE funding for the NGCC, and as the third major new building on the Fermilab site this building will complete the mission-driven infrastructure modernization needs identified in the Campus Master Plan.

## Diversity and inclusion

The international nature of projects that define Fermilab's future elevates the status of the laboratory's core organizational values of diversity and inclusion. Fermilab is committed to attracting, developing, and retaining diverse talent and cultivating an inclusive and productive work environment to support scientific, technological, and operational excellence on the part of its own staff and visiting collaborators from around the world.

To be successful, the laboratory's culture must be conducive to continual learning, dialog, and feedback on diversity and inclusion issues. In conjunction with the laboratory's Diversity and Inclusion Office, the Employee Advisory Group (EAG) and an increasing number of Employee Resource Groups (ERGs) provide forums for dialog and are key to identifying, prioritizing, and advancing diversity and inclusion initiatives from the ground up. Fermilab also plans to implement implicit bias training to educate employees on the impact that subtle attitudes and behaviors have on decision-making in the workplace. Fermilab is actively developing programs to increase the recruitment and retention of under-represented racial minorities, other people of color, women, veterans and individuals with disabilities. New recruiting pipelines for under-represented candidates have been identified and advocates for diversity are being formally included in the processes for hiring and promotion. New opportunities are also being identified to mentor under-represented minorities and women, and to socialize the next generation of employees in issues surrounding workplace diversity and inclusion. Fermilab is forming new collaborations with institutions and organizations such as HBCUs (historically black colleges and universities), HSIs (Hispanic serving institutions), TCUs (tribal colleges and universities), the NSBP (National Society of Black Physicists), NSHP (National Society of Hispanic Physicists), and SWE (Society of Women Engineers) for internships and other professional opportunities.

## Laboratory Directed Research and Development

Fermilab has an LDRD program that supports discretionary research in science and technical areas that are aligned with the DOE-SC Scientific Discovery and Innovation mission and the laboratory's strategic plan. The program maintains the scientific and technical vitality of the laboratory and supports "high-risk, high-payoff" research involving new ideas, new technical concepts, and new technology. Projects are either initiated as a targeted opportunity by the Laboratory Director or are selected via an open call for proposals. The selection committee evaluates proposals and makes recommendations to the Laboratory Director for approval.

LDRD at Fermilab is relatively new, beginning with a mid-year call in FY 2014. For FY 2015, a total of \$2.19M (representing 0.64% of the laboratory's funding) was used to support thirteen projects. Seven additional projects were approved for FY 2016, bringing the level to approximately 1.5% of the laboratory's funding, a scale that is expected to remain relatively constant moving forward. Each approved project is associated with one or more of Fermilab's four core capabilities. Three projects have been completed in FY 2016 and have been successful in satisfying their objectives. One of the completed projects is associated with the accelerator science and technology core capability, and the other two completed projects are associated with the neutrino science major initiative for the particle physics core capability. Other ongoing projects have the potential to bring new areas of research to Fermilab that will support future projects at the laboratory.